

SENSING LUNAR PROPERTIES THROUGH ROTATION AND DEFORMATION. J. G. Williams, D. H. Boggs, J. T. Ratcliff, C. F. Yoder and J. O. Dickey, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109 (e-mail James.Williams@jpl.nasa.gov).

Introduction and Techniques: The interior properties of the Moon influence lunar tides and rotation. Vector rotation is directly sensed by tracking lunar landers. The Lunar Laser Ranging (LLR) experiment has acquired three decades of accurate ranges from observatories on the Earth to four retroreflectors on the Moon. The Lunar Laser Ranging effort is reviewed in [1]. Tides are detected from analysis of laser ranges and radiometric tracking of orbiting spacecraft.

Moment of Inertia: Analyzing tracking data on orbiting spacecraft gives the second-degree gravity harmonics J_2 and C_{22} . From the Lunar Laser data one obtains the moment of inertia combinations $(C-A)/B$ and $(B-A)/C$. Combining the two sets gives C/MR^2 , the polar moment normalized with the mass M and radius R [2].

Elastic Tides: Elastic tidal displacements of the lunar surface are characterized by the lunar (second-degree) Love numbers h_2 and l_2 . Tidal distortion of the second-degree gravity potential and moment of inertia is proportional to the Love number k_2 . The largest periodic tides occur at one month. LLR detects the tidal displacements, $h_2 = 0.033 \pm 0.015$. More accurate is the LLR determination of tidal influences on moments through rotation, $k_2 = 0.025 \pm 0.003$, and the spacecraft determination through variation of gravity field, $k_2 = 0.026 \pm 0.003$ [3]. Accurate determination of Love numbers would help constrain the elastic properties of the deeper zones, including core, where the seismic information is weakest.

Tidal Dissipation: Tidal dissipation causes phase shifts of periodic components of rotation. Tidal Q is a bulk property which depends on the radial distribution of the material Q_s . Tidal Q may depend on tidal frequency, and the effect on rotation is proportional to k_2/Q . LLR detects four dissipation terms and infers a shallow dependence of tidal Q on frequency [4,5]. The tidal Q_s are surprisingly low, but they cannot distinguish the location or extent of the low- Q material. At seismic frequencies low material Q_s were found for the deep zone above the core.

Dissipation at a Liquid-Core/Solid-Mantle Interface: A completely solid core would rotate with the entire Moon, but a fluid core is not similarly constrained. While the lunar equator precesses along the ecliptic plane with an 18.6 yr period and a 1.5° tilt, a fluid core can only weakly mimic this motion. The resulting velocity difference at the core-mantle boundary applies torque and dissipates energy.

The effect observed by LLR is a shift in the node of the forced precession of the equator. Since tidal dissipation also causes a shift, consideration of several dissipation terms is needed to separate the two sources of dissipation. Application of Yoder's [6,7] turbulent boundary layer theory gives limits for core size: ≤ 352 km for molten iron, and ≤ 374 km for the Fe-FeS eutectic. An additional solid inner core is possible.

Ancient Heating: Both tidal dissipation and the core-mantle interaction would significantly heat the Moon when it was closer to the Earth [8,9]. Early dynamical heating could rival radiogenic heating and could promote convection and a dynamo.

Core Ellipticity: The fluid core also exerts torques if the core-mantle boundary is elliptical. Preliminary LLR analysis weakly detects such an effect. Determination of the Love number k_2 is influenced by core ellipticity, and the above value is $\sim 10\%$ less than the value given by fits using a spherical core model.

Free Librations: Lunar free libration modes are subject to damping, and finite observed amplitudes imply recent or active stimulation [10]. The mode analogous to Chandler wobble may be stimulated by eddies at the core-mantle interface [6]. Such activity may be observable as irregularities in the wobble mode.

Future: Important time scales for lunar science observations extend from 1/2 month to decades and geometrical spread of lander locations improves the separation of effects. It is important to continue accurate tracking of multiple lunar retroreflectors. Future landers should consider placing additional retroreflectors or other accurate tracking devices.

References: [1] Dickey et al. (1994) *Science*, 265, 482-490. [2] Konopliv A. S. et al. (1998) *Science*, 281, 1476-1480. [3] Konopliv A. S. et al. (2000) submitted. [4] Williams J G et al. (1999) *Abstracts of Lunar and Planetary Science Conference XXX*, Abs. No. 1984. [5] Williams J G et al. (2000). [6] Yoder C. F. (1981) *Phil. Trans. R. Soc. London A*, 303, 327-338. [7] Yoder C. F. (1995) *Icarus*, 117, 250-286. [8] Williams J G et al. (1999), abstract for New Views of the Moon II. [9] Williams J G et al. (2000) *Abstracts of Lunar and Planetary Science Conference XXXI*, Abs. No. 2018. [10] Newhall X X, and Williams J G (1997) *Celestial Mechanics and Dynamical Astronomy*, 66, 21-30.